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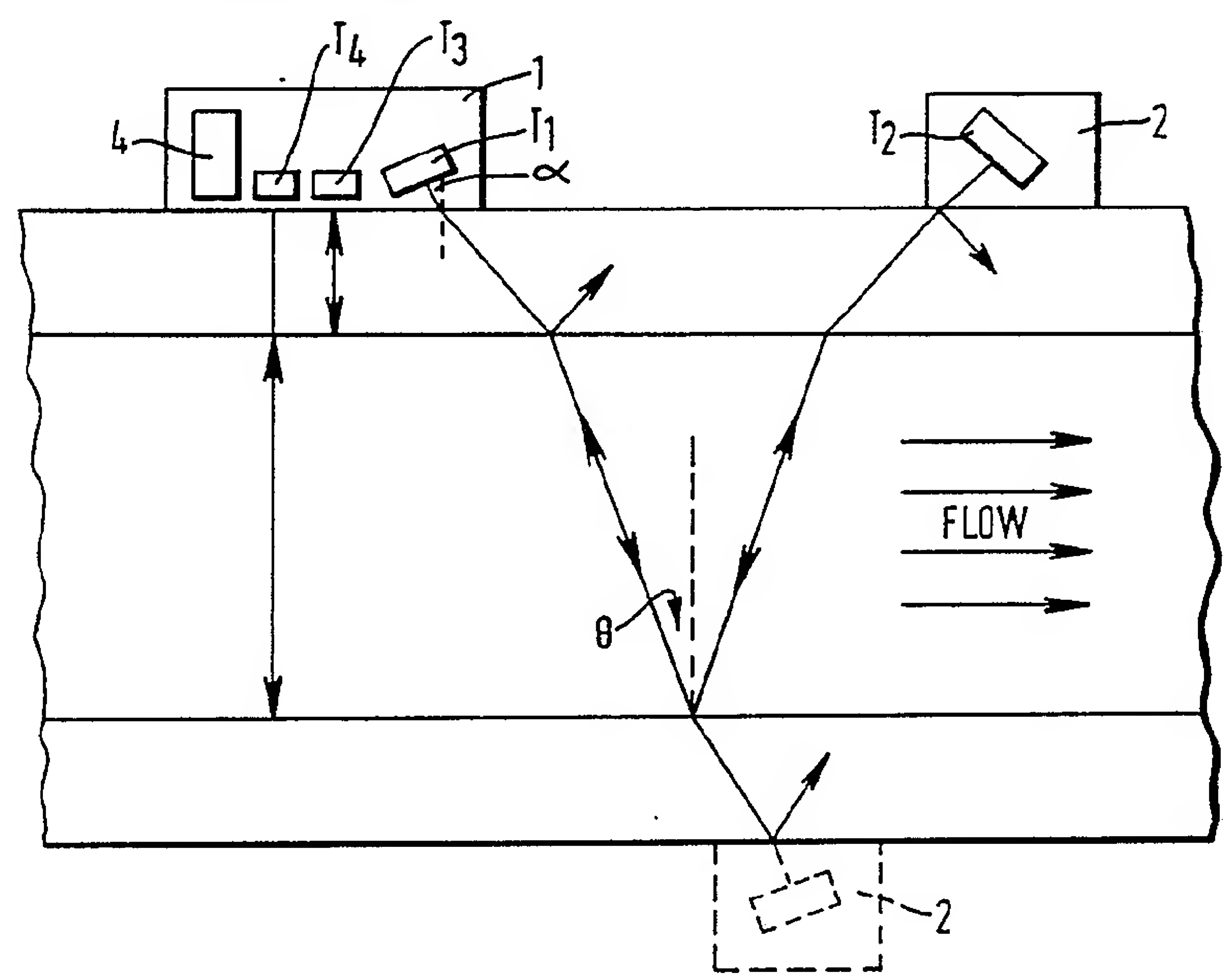

(57) Abstract

An ultrasonic fluid flowmeter has a first mounting block (1) for location at a first station on the external surface of a pipe through which a fluid flows. Two ultrasonic transducers are fixed within the block, the first (T1) being oriented to direct an ultrasonic pulse at a preselected angle to the axis of fluid flow and a second transducer (T4) angled to direct an ultrasonic pulse in a direction perpendicular to the axis of flow. A third ultrasonic transducer (T2) is fixed within a second mounting block (2), for location at a second station on the pipe, and is oriented to intercept the direct or reflected acoustic path of a pulse transmitted by the first transducer. Output signals from the transducers are processed to compute the time of flight of the pulse from first to third transducers and hence the flowrate and the computed flowrate is corrected for variation in the propagation rate of the ultrasound by derivation of a correction factor from the output signal from the second transducer.

ULTRASONIC FLUID FLOWMETER

This invention relates to an ultrasonic fluid flowmeter for non-intrusive monitoring by ultrasound of fluid flow in pipes.

Ultrasonic fluid flowmeters operate on the principle of directing a pulse of ultrasonic energy through a flowing fluid and monitoring the passage of the pulse either by detecting a Doppler shift brought about by the effect of the fluid flow on the pulse, or, alternatively, by measuring the time taken for the pulse to complete its passage through the fluid. It is to the latter type, so-called "time-of-flight' meters, that the present invention relates.

For measurement of the flow of fluid in pipes ultrasonically it is usual for apertures to be cut in the pipe wall for introduction of the ultrasonic transducers directly into contact with the fluid flow to avoid effects of the pipe wall on the measurement. This requirement is clearly disadvantageous in that the design of portable instruments is more or less ruled out. However, a few examples of non-intrusive flowmeters operating on the Doppler effect are known.

The theory on which non-intrusive monitoring of flow by time-of-flight measurement is as follows: A pulse of ultrasonic energy is transmitted from one

transducer to another through the flowing fluid in a direction which may be perpendicular or at an angle to the axis of the flow and the time-of-flight (T_1) of the pulse is measured. A second pulse is then sent along the same path but in the reverse diection and the second time-of-flight (T_2) is measured. One of the pulses will be accelerated by the flow and the other will be retarded. The difference (delta-T) between the two times-of-flight (T_1-T_2) is proportional to the flowrate after suitable correction.

However, to arrive at the absolute value of the flowrate it is necessary to correct the value of delta-T for interfering effects. Using Snell's Law of Refraction and a knowledge of wall thickness, the angle of the ultrasonic pathway to the wall and the rate of propagation of the ultrasound in the material of the pipe wall, a correction factor for wall effect may be calculated. Likewise the rate of propagation of the ultrasound in the fluid will also enable a correction factor to be derived. It will be understood that these factors vary between locations and with time. Thus the material of the pipe wall and its thickness, which is not, of couse, apparent from outside the pipe, and the density of the fluid, which may vary with changes in composition and with temperature, affect the measurement and require correction of the observed time-of-flight and delta-T.

An object of the present invention is to provide a non-intrusive ultrasonic flowmeter operating on the principle of time-of-flight measurement.

According to the present invention there is provided an ultrasonic fluid flowmeter comprising;

(a) a first mounting block for location at a first station on the external surface of a pipe carrying a flow of fluid;

(b) a first ultrasonic transducer fixedly housed within the block and oriented to direct an ultrasonic pulse at a preselected angle to the axis of fluid flow;

(c) a second ultrasonic transducer within the first mounting block and oriented to direct an ultrasonic pulse in a direction perpendicular to the axis of flow;

(d) a second mounting block for location at a second station on the pipe;

(e) a third ultrasonic transducer fixedly housed within the second mounting block and oriented to intercept the direct or reflected acoustic path of a pulse transmitted by the first transducer; and,

(f) means for receiving and processing output signals from first, second and third transducers whereby the time of flight of the pulse from first to third transducers is computed and converted to flowrate and an output signal from the second transducer is processed to modify the conversion in response to any changes in propagation rate represented by changes in the output signal from the second transducer.

Preferably the flowmeter also includes means within a mounting block responding to changes in temperature and means for modifying the measured flowrate in response thereto.

The flowmeter may also include a fourth ultrasonic transducer for measurement of the wall thickness of the pipe and modifying the measured flowrate in response thereto.

An embodiment of the present invention will now be described, by way of illustration, with reference to the accompanying drawings of which:

Fig.1 is a schematic representation of a section through a pipe having a flowmeter of the invention mounted on its external surface; and,

Fig.2 is a block diagram representing the means for receiving and processing signals from the transducers to give an indication of flowrate.

Referring to Fig.1, a first mounting block 1 and a second mounting block 2 are provided for clamping to the external surface of a pipe 3 carrying a flow of fluid.

Mounting block 1 houses an ultrasonic transducer, referenced as T_1 in Fig.1, which is fixedly held at an angle to the axis of flow of the fluid so as to direct an ultrasonic pulse at an angle across the flow in the direction indicated in Fig.1.

The second mounting block 2 also houses a

transducer T_2 which is fixed therein at an angle to intercept the beam from transducer T_1. An alternative location for mounting block 2 is shown in broken lines in Fig.1.

Mounting block 1 also houses transducers T_3 and T_4 oriented to direct pulses perpendicular to the axis of flow, and temperature sensor 4.

Fig.2 shows a block diagram of the signal handling electronics used to process output signals from transducers T_1 to T_4 and sensor 4, to give an output of the fluid flowrate.

The precise calculation of the flowrate requires calculation of the angles of refraction of the pulse and the following parameters are rquired for that calculation:

(i) Transmission angle (a)

In the flowmeter of the present invention the transmission angle "a" is fixed by the housing of the transducers T_1 and T_2 in their respective mounting blocks 1 and 2.

(ii) Transducer Propagation Rate (T)

This parameter varies with temperature. It is an important parameter since it is required to allow calculation of the fluid angle using Snell's Law. Temperature is is measured by sensor 4 in mounting block 1.

(iii) Wall Propagation Rate (W)

This parameter enables calculation of the beam path in the wall of the pipe. The propagation rates for a variety of pipe materials are held as a look-up table in the memory of the instrument.

(iv) Fluid Propagation Rate (F)

This parameter is dependent on characteristics of the fluid such as density and temperature. It is required for the calculation of the the beam angle/path.

(v) Outside Pipe Diameter

Outside diameter (O_d)is readily measurable on site by an operator of the flowmeter. This parameter is necessary for calculation of the pipe inside diameter (I_d), that is, O_d - 2 x wall thickness = I_d.

In the flowmeter of the present invention as illustrated in Fig.1, transducer T_1, in conjunction with transducer T_2 produces output signals which are processed to obtain the total time delay brought about by (a) the transducer material (b) the pipe wall and (c) the fluid flow. The signal processing also produces a delta-T flow signal by measurement and calculation.

Transducer T_3 is used to measure the wall thickness. This calculation requires the operator to input to the instrument the outside diameter of the pipe and its material of fabrication, the acoustic properties of materials being readable from memory by the instrument.

Transducer T_4 is used to measure fluid propagation rate.

The temperature sensor 4 measures the temperature of the material of the transducers within the mounting block 1, to be used in the calculation the propagation rate of the transducer material, which varies with temperature, and thus enabling calculation of the fluid angle, θ.

The principle of operation will now be described with reference to Fig.1.

By exciting the piezoelectric crystals within the transducers, ultrasound passes through the pipe wall and across the flow of liquid from at an angle θ to the axis of flow and may be detected or reflected at the opposite wall as shown by the alternative positions of the second mounting block 2 containing transducer T_2. The time of flight of the ultrasound from T_1 to T_2 is derived as follows:

$$t_{1-2} = I_d/\cos\theta \times 1/c+V\sin\theta \qquad (1)$$

$$t_{2-1} = I_d/\cos\theta \times 1/c-V\sin\theta \qquad (2)$$

$$dT = t_{1-2} - t_{2-1}$$

$$= I_d \times 2V\sin\theta / \cos\theta \times c^2 - (V\sin\theta)^2 \qquad (3)$$

in which; t_{1-2} is the time of ultrasound travel from transducer T_1 to transducer T_2;

t_{2-1} is the time of ultrasound travel from transducer T_2 to transducer T_1;

I_d is the pipe internal diameter;

c is the rate of ultrasound propagation in the fluid;

V is the flow velocity;

θ is the fluid angle; and,

dT is the time difference.

Since $(V\sin\theta)^2$ is insignificant with respect to the term c^2 it can be ignored.

Therefore :

$$\text{Time Difference } (dT) = I_d.2V.\tan\theta / c^2 \qquad (4)$$

As c^2 changes according to variations in density or temperature of the fluid, it must be eliminated from equation (4) to ensure stable performance. Therefore, by multiplying both sides of equation (4) by c^2, the solution results in velocity V being proportional to dt/T^2.

Now, since $c^2 = I_d^2/T^2$

$$dT.I_d^2/T^2 = I_d.2V\tan\theta$$

$$\text{Therefore: } dT/T^2 = 2V\tan\theta/I_d \qquad (5)$$

The flowmeter of the present invention is designed to monitor dT/T^2 as well as to detect and measure accurately the very minute time differences involved.

Having defined the relationship between flow velocity (V) and time, two other factors have to be taken into account in order to modify the readings for

the effect of the pipe wall on a clamp-on system flowmeter to obtain accurate results without resorting to volumetric calibration.

(i) As can be seen from Fig..1, refraction in the various media encountered by the ultrasonic beam controls the fluid angle (Θ) which, according to Snell's Law is defined by the equation (6).

$$V_C/\sin\theta = V_T/\sin\alpha = \text{constant} \qquad (6)$$

where: V_C = liquid sound velocity;

V_T = transducer sound velocity;

α = transducer injection angle; and,

O = liquid beam angle.

(ii) The effects of flow profile variation which are directly related to the Reynolds Number have also to be taken into account. Here again the flowmeter reading and the Reynolds Number are related mathematically and thus only processing of the collected data is required.

CLAIMS

1. An ultrasonic fluid flowmeter comprising;

(a) a first mounting block for location at a first station on the external surface of a pipe carrying a flow of fluid;

(b) a first ultrasonic transducer fixedly housed within the block and oriented to direct an ultrasonic pulse at a preselected angle to the axis of fluid flow;

(c) a second ultrasonic transducer within the first mounting block and oriented to direct an ultrasonic pulse in a direction perpendicular to the axis of flow;

(d) a second mounting block for location at a second station on the pipe;

(e) a third ultrasonic transducer fixedly housed within the second mounting block and oriented to intercept the direct or reflected acoustic path of a pulse transmitted by the first transducer; and,

(f) means for receiving and processing output signals from first, second and third transducers whereby the time of flight of the pulse from first to third transducers is computed and converted to flowrate and an output signal from the second transducer is processed to modify the conversion in response to any changes in propagation rate represented by changes in the output signal from the second transducer.

2. An ultrasonic fluid flowmeter according to claim 1, which also includes means within a mounting block responding to changes in temperature and means for modifying the measured flowrate in response thereto.

3. An ultrasonic fluid flowmeter according to claim 1 or claim 2, which also includes a fourth ultrasonic transducer for measurement of the wall thickness of the pipe and modifying the measured flowrate in response thereto.

4. An ultrasonic fluid flowmeter according to claim 1 or claim 2 or claim 3, in which the means for receiving and processing output signals includes a data store of acoustic properties of materials of fabrication of pipes, accessible on input of the identity of the material of fabrication by an operator.

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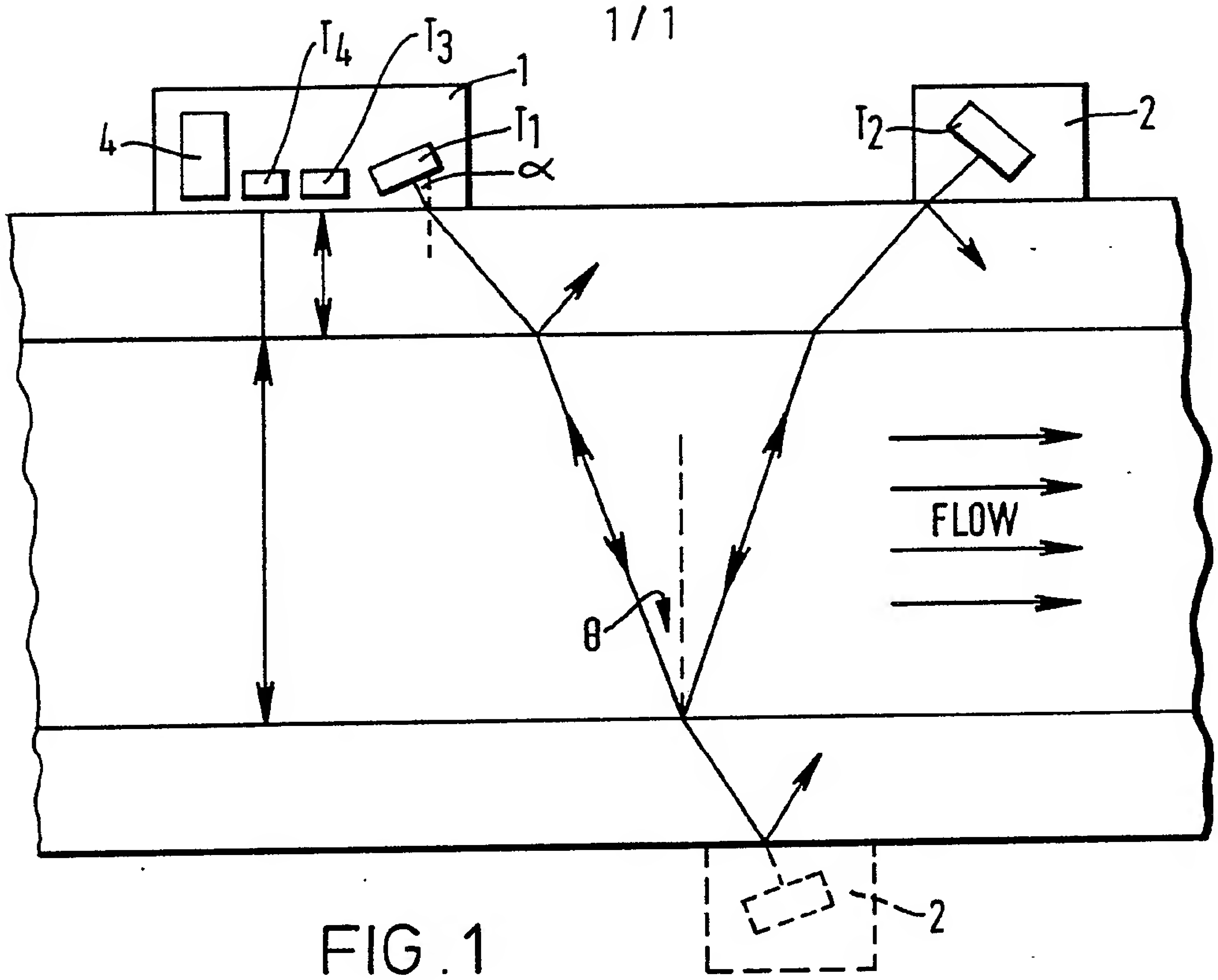
T4
T3
1
4
T1
α
T2
2
FLOW
θ
2

FIG.1

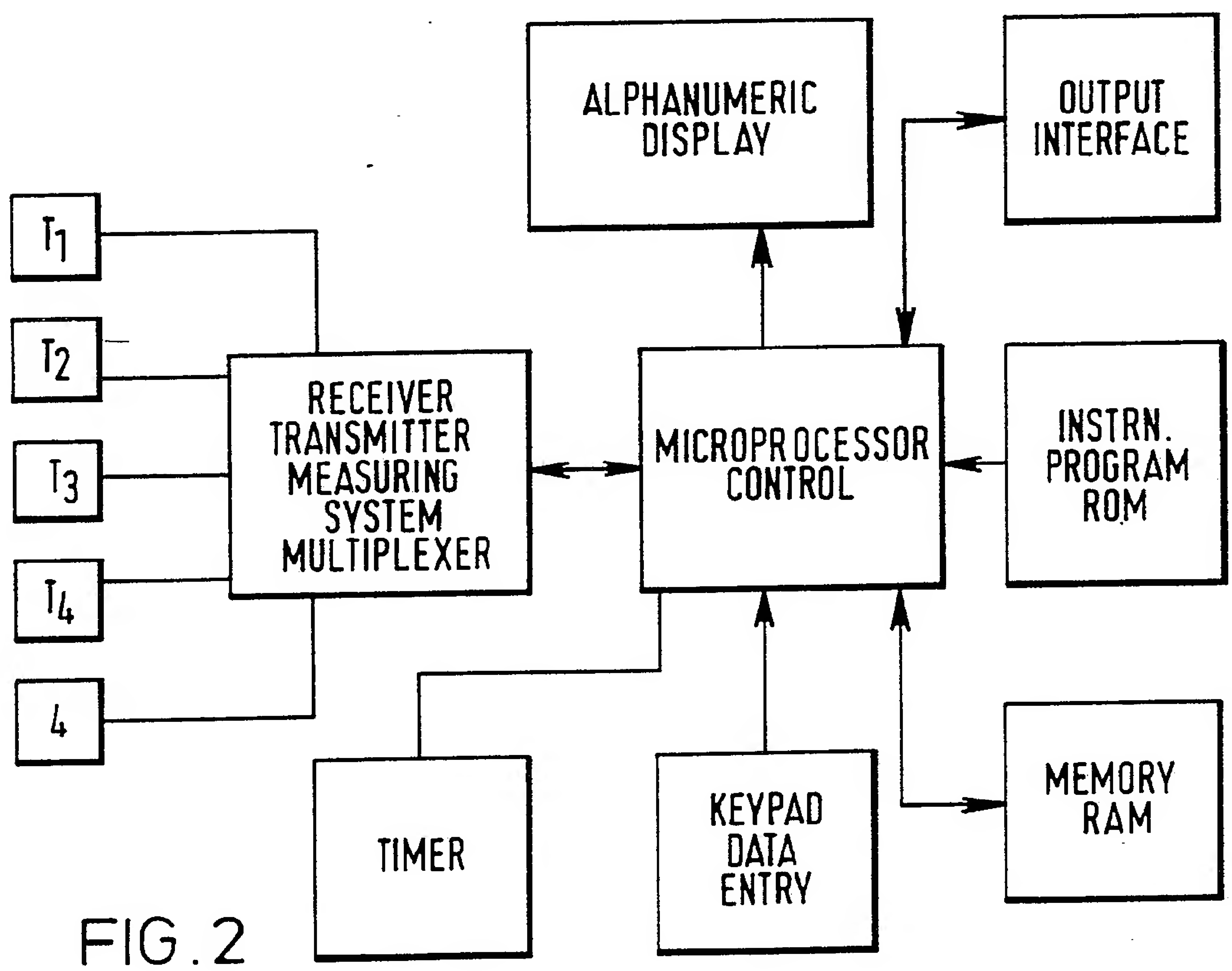
ALPHANUMERIC DISPLAY
OUTPUT INTERFACE
T1
T2
T3
T4
4
RECEIVER TRANSMITTER MEASURING SYSTEM MULTIPLEXER
MICROPROCESSOR CONTROL
INSTRN. PROGRAM ROM
TIMER
KEYPAD DATA ENTRY
MEMORY RAM

FIG.2

INTERNATIONAL SEARCH REPORT

International Application No PCT/GB 88/00328

I. CLASSIFICATION OF SUBJECT MATTER (if several classification symbols apply, indicate all) [6]

According to International Patent Classification (IPC) or to both National Classification and IPC

IPC^4: G 01 F 1/66

II. FIELDS SEARCHED

Minimum Documentation Searched [7]

Classification System	Classification Symbols
IPC^4	G 01 F; G 01 P; G 01 S

Documentation Searched other than Minimum Documentation to the Extent that such Documents are Included in the Fields Searched [8]

III. DOCUMENTS CONSIDERED TO BE RELEVANT [9]

Category *	Citation of Document, [11] with indication, where appropriate, of the relevant passages [12]	Relevant to Claim No. [13]
X Y	FR, A, 2077827 (THOMSON-CSF) 5 November 1971 see page 1, lines 5-18; page 1, line 34 - page 2, line 10; page 3, lines 14-35; figures 2,3	1 2,3
X	FR, A, 2077968 (THOMSON-CSF) 5 November 1971 see page 1, lines 1-9; page 5, line 7 - page 6, line 16; page 6, line 30 - page 7, line 28; figure 4	1
X	Electronique Industrielle, no. 133, May 1970 A. Courty et al.: "Debimetre à ultrasons", pages 264-269 see page 266, left-hand column, line 1 - right-hand column, line 27; page 267, left-hand column, lines 1-22; figure 2	1

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* Special categories of cited documents: [10]
- "A" document defining the general state of the art which is not considered to be of particular relevance
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- "X" document of particular relevance; the claimed invention cannot be considered novel or cannot be considered to involve an inventive step
- "Y" document of particular relevance; the claimed invention cannot be considered to involve an inventive step when the document is combined with one or more other such documents, such combination being obvious to a person skilled in the art.
- "&" document member of the same patent family

IV. CERTIFICATION

Date of the Actual Completion of the International Search	Date of Mailing of this International Search Report
1st August 1988	- 1. 09. 88
International Searching Authority	**Signature of Authorized Officer**
EUROPEAN PATENT OFFICE	P.C.G. VAN DER PUTTEN

International Application No. PCT/GB 88/00328

III. DOCUMENTS CONSIDERED TO BE RELEVANT (CONTINUED FROM THE SECOND SHEET)

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Y	Patent Abstracts of Japan, volume 4, no. 110 (P-22)(592), 8 August 1980, & JP, A, 5569020 (TOKYO SHIBAURA DENKI K.K.) 24 May 1980 see abstract	2,3
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A	US, A, 4397194 (DANIEL J. SOLTZ) 9 August 1983 see column 4, line 26 - column 5, line 4; figure 1	1,3
A	GB, A, 861584 (TECHNICAL CERAMICS LTD) 22 February 1961 see page 1, lines 14-19; page 1, line 80 - page 2, line 17; page 2, lines 84-88, 120-122; figure 1	1
A	EP, A, 0200896 (BADGER METER INC.) 17 December 1986 see abstract; figure 1	1

ANNEX TO THE INTERNATIONAL SEARCH REPORT ON INTERNATIONAL PATENT APPLICATION NO.

GB 8800328
SA 22039

This annex lists the patent family members relating to the patent documents cited in the above-mentioned international search report.
The members are as contained in the European Patent Office EDP file on 23/08/88
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US-A- 4397194	09-08-83	None	
GB-A- 861584		None	
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		US-A- 4633719	06-01-87

For more details about this annex : see Official Journal of the European Patent Office, No. 12/82